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Electrical characteristics of a plasma arc torch.

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ELECTRICAL CHARACTERISTICS OF A PLASMA ARC TORCH

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ELECTRICAL CHARACTERISTICS

OF A PLASMA ARC TORCH

by

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TABLE OF CONTENTS

LIST OF FIGURES

F O R E W A R D

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Abstract

The specific problem in this investigation is the study of the electrical characteristics of a plasma torch. Plasma torches are not a recent invention; however no development was done until the mid 1950's.

The discussion of the plasma torch in this paper includes the basic design considerations for the torch itself, the method of operation including limitations there to, and some results obtained from the operation of the torch. The results presented include the voltage-current characteristics for different nozzle lengths and different gap lengths. Some relative temperature measurements with two different nozzles, the stability of the arc, and other relative data are also presented. The main problem involved in the operation of the torch, excessive anode heating, is discussed together with appropriate anode cooling suggestions and time limitations on continuous operation of the torch.

PART I

INTRODUCTION

A. Introduction and Historical Review

A plasma is defined as an ionized state of matter in which the concentrations of positive and negative ions are equal. Plasmas vary from low temperature and therefore low ion concentrations as in the fluorescent lamp through medium temperature with resulting medium ion concentrations as found in the electric welding arc to relatively high temperature and therefore high ion concentrations, as found in the plasma torch.

The plasma torch is a device presently capable of producing temperatures of the order of 60000°F [2*] without combustion. It is not a new device as there are comments on it dating back to the early 1900's.[9] However, there was no application for the device at that time and therefore, no work was done on it. Additionally, techniques required to fabricate highly refractory critical components for continuous operation at high power levels had not been developed.

In the mid 1950's, a very high temperature heat source was required for the study of the nose cone re-entry problem. When a nose cone re-enters the earth's atmosphere, the heat generated by the friction between the cone and the adjacent air causes the air to disassociate into a plasma.

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*Throughout this thesis, superscript numbers refer to the similarly numbered items in PART VII, LITERATURE CITED, used in support of statements preceding the superscript numbers.

This heating also causes ablation of the nose cone and serious heating problems with the components in the cone. The plasma torch was developed to provide a high temperature heat and plasma source so that heat transfer and ablation studies could be made of nose cone models of various shapes.

After development was under way toward using this device as a laboratory heat source, others[2] began to envision some diverse uses for it. The very high temperatures existing within the device makes it possible to use it for spraying one substance on to another. The object to be sprayed is placed in front of the torch and the material, to be deposited, is put in the torch as a finely ground powder. The intense heat in the plasma melts this immediately, making it possible to spray, as with a paint spray gun, such high melting point materials as tungsten carbide (2850°C) tungsten (3350°C) and other materials of this type.

In addition to the spraying of one substance on to another, it is now possible to manufacture parts from material that is normally considered to be very difficult to work. The material to be fabricated is put in the torch as a finely ground powder and sprayed on a form. The form is then removed and the part is complete. Thicknesses can be quite accurately controlled with this process.

High speed cutting of metal plate is also easily accomplished with a slightly different type of plasma torch.

One inch steel plate has been cut at twice the speed and one-half the cost of conventional oxygen cutting.[12] The resultant edge was quite smooth and free from foreign material.

The largest part of the recent experimental work with the plasma torch has been done by personnel primarily interested in the heating characteristics of the device. Very recently, however, Thomas and Gates,[14] have reported on the electrical characteristics of the plasma torch. They investigated the electrical characteristics of arcs in Argon and in Helium between a brass cathode and a copper anode, and between a tungsten cathode and a copper anode. The range of arc currents reported was 0-3000 amps DC and the arc gaps ranged up to two inches.

It is the purpose of this paper to investigate the electrical characteristics of the plasma arc torch with a different type of swirl chamber than that used above and different electrodes. The effects of the various torch parameters connected therewith, including gap, gas type, gas flow, and anode length will be investigated and discussed.

B. Statement of the Problem

The Electrical Engineering Department of the Rensselaer Polytechnic Institute decided in the early fall 1959 to expand its plasma research activities to include the plasma arc torch. An informal inquiry was made to an organization which manufactures these devices commercially. The price quoted by that organization for the torch power supply and control console was about $5,000. A suitable welding generator and auxiliary equipment was already available at R.P.I., and it was felt that valuable knowledge could be gained from designing and building the torch from the beginning. Therefore, it was decided that the torch would be designed and built at R.P.I.

The torch built by Thomas and Gates[14] was designed for operation at power levels of the order of three megawatts. Consequently, the anode cooling system and the swirl chamber among other parts required considerable machining.

The torch to be built at R.P.I. was to be powered by a welding generator with a continuous output of about 25 KW and it was felt that a satisfactory torch could be built for this power level which would not require precise machining. This would reduce the initial cost of the torch and would facilitate modifications and repairs as the investigation progressed.

It was decided that the R.P.I. torch would have non-consumable electrodes, be of simple mechanical construction, and be capable of continuous operation for periods of 15-30 seconds at 15-25 KW input. The stability of the arc, reliability of the torch, the volt-ampere characteristic curves, temperature and noise were to be investigated as the gas type, flow, arc gap and anode length were varied.

It was the writer's desire to learn more about arcs and plasmas in general and this new device in particular that caused him to undertake this project. Additionally, it was desired to block in the limits of the various parameters including gas type, gas flow, arc gap and anode length.

PART II

THEORY

A. Arcs, Plasmas and Temperature

1. Arcs

The electric arc is a self-sustained discharge having a low voltage drop and capable of supporting large currents.[3] An arc may be established by the separation of current carrying contacts or by transition from a different type, and higher voltage discharge. In this paper, consideration will be given to the second type only. Before discussing arcs further, some things should be said about ionization. Ionization is the separation of an electrically neutral atom into a negative electron and a heavy positive ion. To do this, one must impart sufficient energy to the neutral atom to remove the electron from the influence of the nucleus. This energy is called the ionization potential. If, when they are formed, the electron and positive ion are in a constant electric field, between electrodes, each will be accelerated to the appropriate electrode. During this travel, the electric field is imparting energy to the particles. Should either of these particles, after having its energy level raised above the ionization potential by the electric field, collide with a neutral atom it may impart sufficient energy to that atom to ionize it. This is particularly true in the case of the electron. From this, it is easy to envision an "electron avalanche" started by

the ionization of a gas molecule between two electrodes. The electrons and ions carry the full arc current. It should also be pointed out that the ionization potential is different for different gases. After the initial breakdown of the gap between the electrodes, there are several additional sources from which electrons are generated to maintain the arc. Upon arrival at the cathode, the heavy positive ions surrender their energy. This energy is available to heat up the cathode thus causing emission. When the electrons arrive at the anode they give up their energy. It is possible that electrons may be released from the anode as a result of the impact of one electron. As was mentioned before, the heavy ions are not as efficient ionizers as are the electrons. In their trip to the cathode, they do collide with, and impart some energy to the neutral atoms. This will raise the energy, and the apparent temperature of the neutral atom, making future ionization easier. All of these methods furnish free electrons to the discharge. Therefore, once started, the discharge will maintain itself as long as the field remains.

2. <u>Plasmas and Temperature</u>

As was stated earlier in this paper, a plasma is defined as an ionized state of matter containing equal concentrations of positive ions and electrons. When the electrons and ions of a plasma recombine, they give up the energy obtained upon ionization. This energy will be given

up in the form of radiation, both heat and light. This heat of recombination is the useful heat generated by the plasma torch.

The temperature of a plasma is a rather complicated quantity, As shown,[6]

$$T = \frac{MC^2}{3k} \quad \text{and} \quad E = \frac{MC^2}{2}$$

Where T is the average temperature of the "gas" in degrees Kelvin, C^2 is the mean square velocity in CM^2/SEC^2, k is Boltzmann's constant and E is the energy of the particle in question. Therefore, the quantity temperature can be related to the mean square velocity of the gas. Considering a plasma as a mixture of three gasses: electrons, ions, and atoms, it is readily apparent that if all particles have the same energy, they will all have the same temperature. This situation is defined as thermal equilibrium. It should be noted that even though the temperature and energy are the same, the velocity will vary inversely as the square root of the mass. The neutral atoms will not be affected by the field however, as the ions and atoms are the same size, the ions will have frequent collisions with the atoms and will thus raise the energy and temperature of the neutral atoms. The electrons will have less frequent collisions and thus attain their higher velocity.

B. Arc Volt-Ampere Characteristics

The voltage drop across a D.C. arc at atmospheric pressure is well defined and consists of three regions. Extending out from the cathode a short distance is the cathode drop region. The voltage across this region is of the order of the least ionization potential of the gas in which the arc burns, and there is a very high positive ion space charge in this region.[4] The second region is the positive column or plasma which connects the cathode drop region with the anode drop region. This region is characterized by a plasma with a small linear voltage gradient and high temperature. The third region is the anode drop region. This extends a short distance from the anode and there is a high negative space charge at the anode end of the anode drop region. This is caused by the electrons collected by the anode. Each electron arriving at the anode gives up energy in the form of heat equal to the anode potential drop plus the equivalent of the work function of the anode.[5] This, plus the heat radiated to the anode from the plasma, heats the anode and was a serious problem with the torch under discussion.

The literature is full of reports of investigations into the volt-ampere characteristics of electric arcs at atmospheric pressure. In 1902, Ayrton[1] reported that the voltage across carbon electrodes separated by 1 to 7 millimeters decreased rapidly as the current was increased from

2 amperes to about 15-20 amperes. Above about 20 amperes, the arc became noisy, and the voltage increased slightly with increasing current. Nottingham[11] confirmed the basic shape of these curves. This work was only done for currents below 30 amperes. Finkelnburg[7] confirmed the results and carried the current to 100 amperes with carbon electrodes.[8] He concluded that the decisive phenomena of the carbon arc are determined by the conditions in the anode drop region and that the increase of total arc voltage in the high current carbon arc is caused by an increase of the anode drop with increased current. He also noted that a crater always formed on the positive carbon electrode. More recently, Jones, Skolnik, and Kowenhaven[10] investigated the electric arc between tungsten electrodes, separated up to 1.0 inches for currents up to 100 amperes at atmospheric pressure, in Argon and again in Helium. They reported the same decreasing characteristic but reported no rising characteristic below 100 amps, the limit of their investigations. Winsor[13] reported a rise in arc voltage with arc current above about 50 amps between a tungsten electrode and a steel plate in an Argon atmosphere.

These characteristic curves will be discussed again later in this paper.

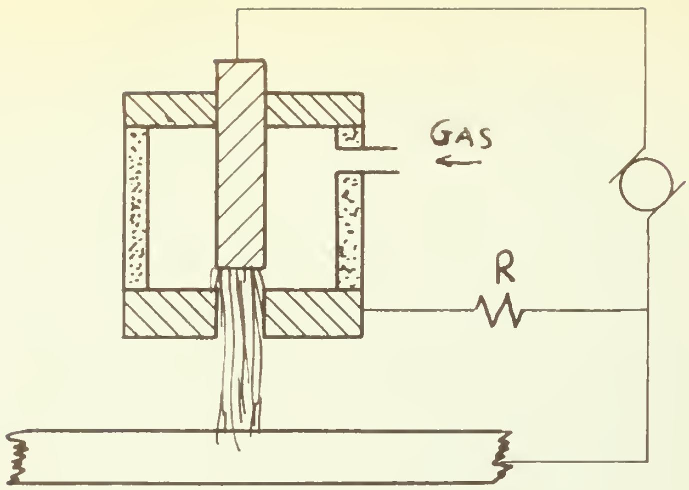
C. Types of Plasma Torches

A plasma torch is, as was said previously, a device capable of creating high temperatures. To do this an arc is established by an auxiliary device in a DC field between two electrodes. Gas is passed through the arc wherein the gas molecules are ionized. The gas pressure inside of the torch then forces this plasma out the front of the torch. Upon reaching the cooler atmosphere outside of the torch, the electrons and ions recombine giving up energy. The part of this energy given up as heat is the useful heat generated by the torch.

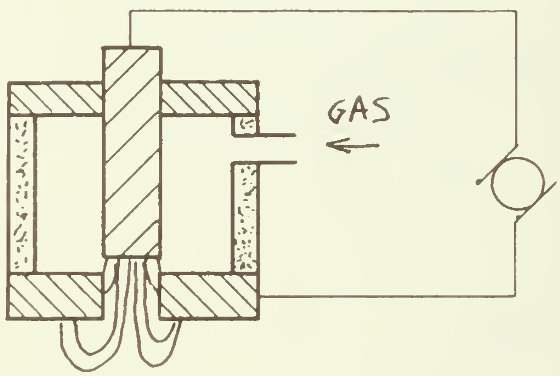
There are two types of plasma arc torches. These are the transferred arc torch and the non-transferred arc torch. Figure I shows these two types of torches.

In the transferred arc torch, the arc is originally struck within the torch. After establishment, the arc is transferred to the work. This type of torch is especially useful in cutting.

In the non-transferred arc torch, the arc is struck and maintained almost completely within the torch. Usually, only the plasma is available for productive work. This type of torch is especially suited for spraying and as a high temperature heat source.



TRANSFERED ARC PLASMA TORCH



NON-TRANSFERED ARC PLASMA TORCH

FIG. I

PART III

EXPERIMENTAL PROCEDURES

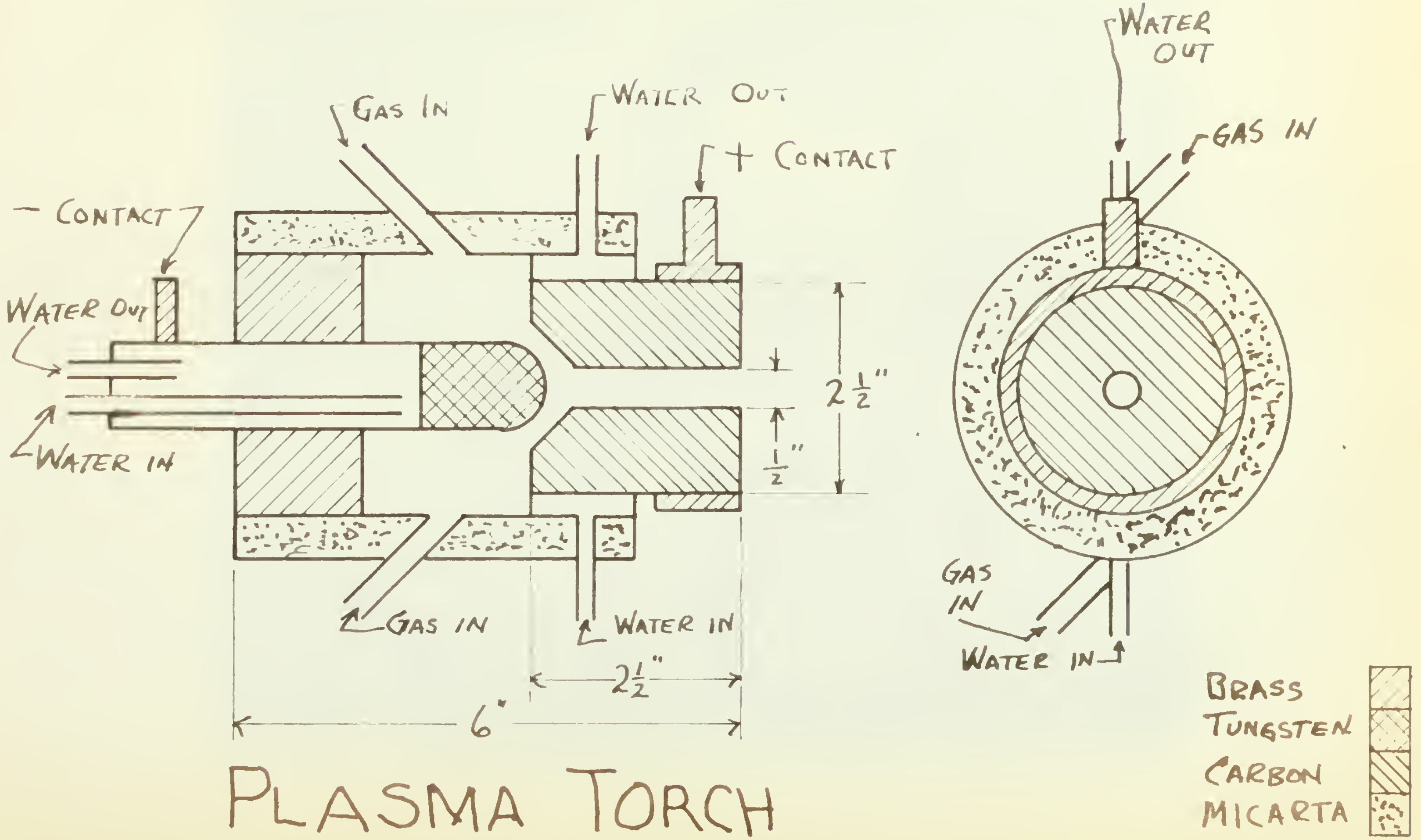
A. Design of Subject Torch

The design of the torch was given very careful consideration. The required torch was to have non-consumable electrodes, if possible, be of simple mechanical construction to facilitate the change of components and ease of fabrication;and to be able to reproduce data. Prior to completing the final design, two field trips were made to organizations presently involved in plasma torch research. These were The Thermal Dynamics Corporation, Lebanon, New Hampshire, and the AVCO Manufacturing Corporation, Lawrence, Massachusetts. In both cases, personnel working with the torch were very helpful and offered valuable suggestions. Additionally, the torch design used by Thomas and Gates[14] was examined carefully.

In an attempt to satisfy the requirement for non-consumable electrodes, Tungsten was chosen for the cathode and carbon for the anode. Any metal or carbon could have been used for the cathode but it was felt that Tungsten would outlast other metals and perform the electron emission functions of the cathode better than carbon. Likewise, a metal could have been used for the anode in place of carbon. Initially, it was hoped that if a sufficiently large piece of carbon were used, no auxiliary cooling of the anode would be required. On this basis as well as its

ability to withstand high temperatures, carbon was chosen for the anode.

At this point, all materials for the fabrication and testing of the torch were available except the insulating sleeve which forms the body of the torch. An attempt was made to use an available bakelite tube but this did not give satisfactory results as the bakelite overheated badly in a few seconds. The tests did indicate the urgent requirement for auxiliary anode cooling and some changes in the gas system. In this first model, the gas inlet ports were installed perpindicular to the body of the torch. At the conclusion of the tests, the anode was examined and it exhibited uneven erosion. It was felt that the uneven erosion was caused by the gas not swirling the arc properly. To correct these deficiencies, it was decided to make the body of the torch from Micarta due to its excellent heat resistant qualities and to install the gas ports at 45° angles to the axial and transverse axes of the torch. This tends to rotate the arc giving even wear to the electrodes. After inclusion of a water jacket for anode cooling, the design proved successful. No dimensions were found to be critical, but axial symmetry is important for even burning. The final design as actually constructed and tested is shown in Figure IIA. Figure IIB shows the plasma arc torch in operation.



PLASMA TORCH

FIG II A

HALF SCALE

PLASMA TORCH IN OPERATION

Figure IIB

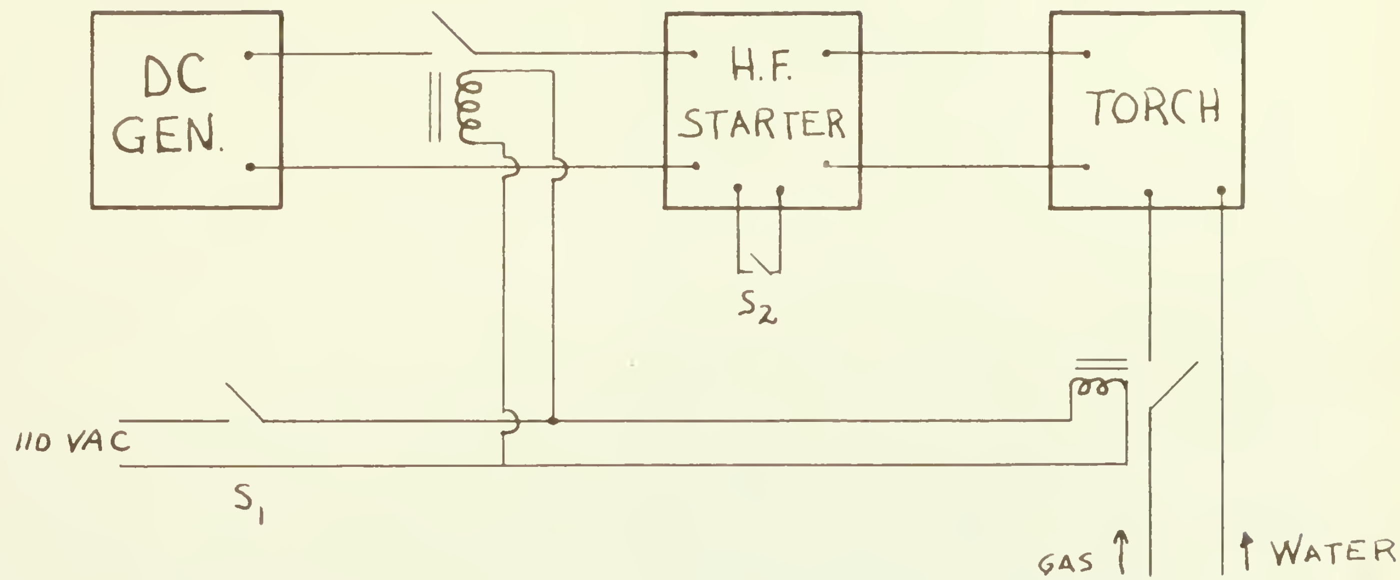
B. Apparatus and Procedure

The wiring diagram for the plasma torch set up is shown in Figure III. None of the auxiliary equipment is critical except that the DC power supply must have a drooping voltage characteristic. The DC power supply used is a Lincoln Welding generator rated at 600 amperes output with current and voltage control and a no-load voltage of about 115 VDC. The high frequency starter is a standard P&H high frequency welding arc starter. The gas flowmeter is an Oxweld L-2I Critical Orifice Flowmeter equipped with Orifice #31. At 11 psig on the upstream gage, approximately 4 cfm of argon enters the torch. The meters used are standard Weston meters, 0-150 VDC and 0-50 millivolts with an 800 ampere shunt.

In obtaining the data reported herein, the procedure listed in Appendix I was used. The first data taken is shown in Figure IV. The gap was set and then the points were taken. After taking all of the points for a particular curve, the gap was rechecked and the inside of the anode was checked for wear.

After taking the data shown in Figure IV, an unsuccessful attempt was made to use Helium instead of Argon. It was not possible to produce a stable arc at any gap setting up to $\frac{1}{2}$".

After the unsuccessful attempt with Helium, the anode was shortened from $3\frac{1}{2}$" to $2\frac{1}{2}$" and the data shown in



WIRING DIAGRAM FOR PLASMA TORCH SET UP

FIG III

Figure V were taken. By this time a silvery-white coating, later believed to be tungsten oxide was beginning to coat the cathode and it was impossible to start the torch at gaps greater than $\frac{1}{4}$". It was felt that this coating was caused by turning off the gas supply simultaneously with the electric power to the arc. This allowed the hot tungsten cathode to cool in an atmosphere of air causing the tungsten oxide to form. An attempt to polish this oxide off was made however, this apparently contaminated the cathode and reproducible results were not obtained after that. Throughout the tests, the torch was run continuously for periods up to 30 seconds. It would have been possible to run it longer except for excess anode heating. If the torch were left on in excess of 30 seconds, the water in the anode cooling jacket would boil.

PART IV

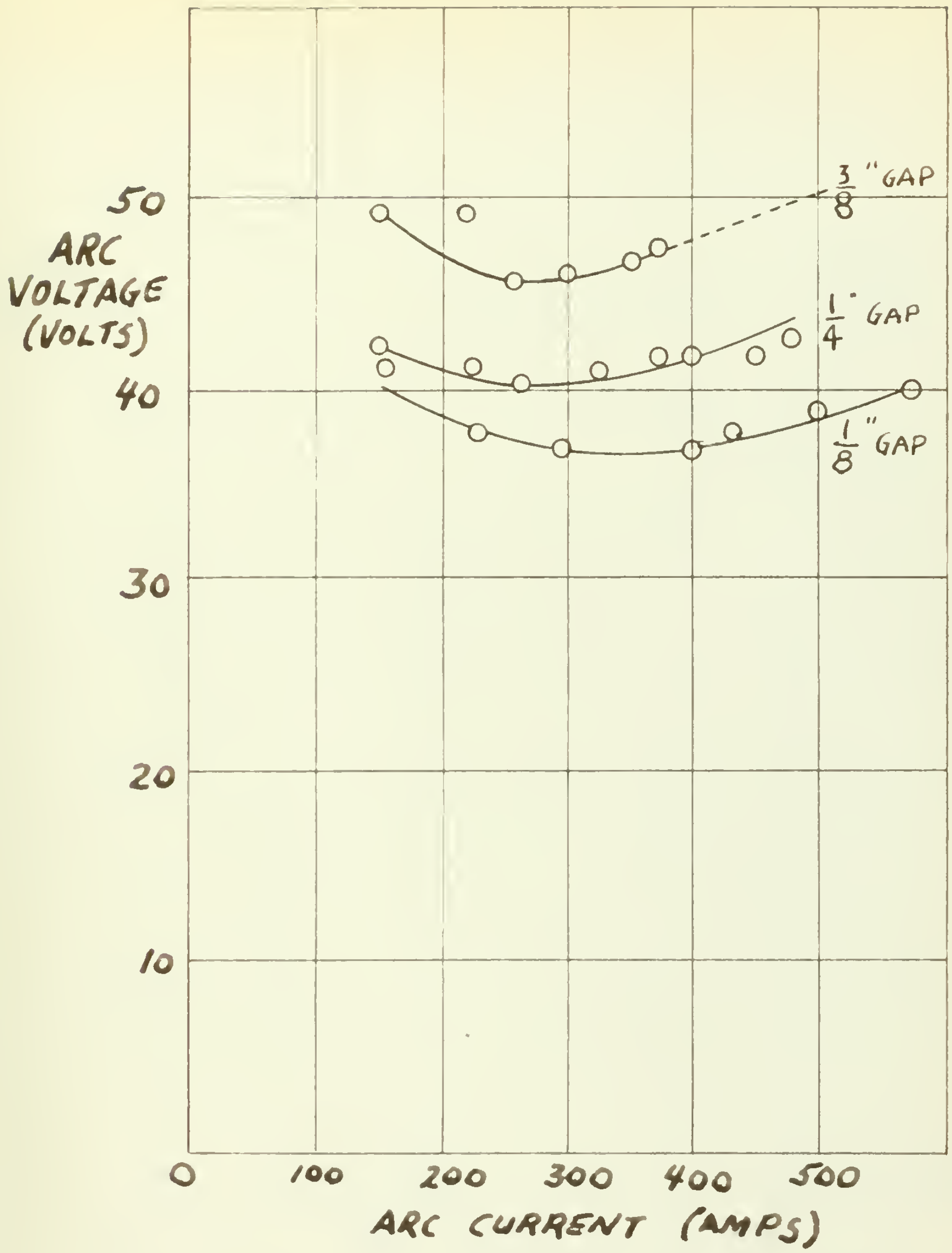
RESULTS

At first, an attempt was made to use an argon gas flow of 1 CFM. This was unsuccessful at all gap lengths as the arc did not rotate and thus eroded the anode unevenly. Additionally, apparently also due to the low gas flow, excessive anode heating made it impossible to run the torch for more than 15 seconds.

Attempts were made to operate at various gaps and a gas flow of 6 CFM but these were also unsuccessful. The gas flow was too high and blew the arc out.

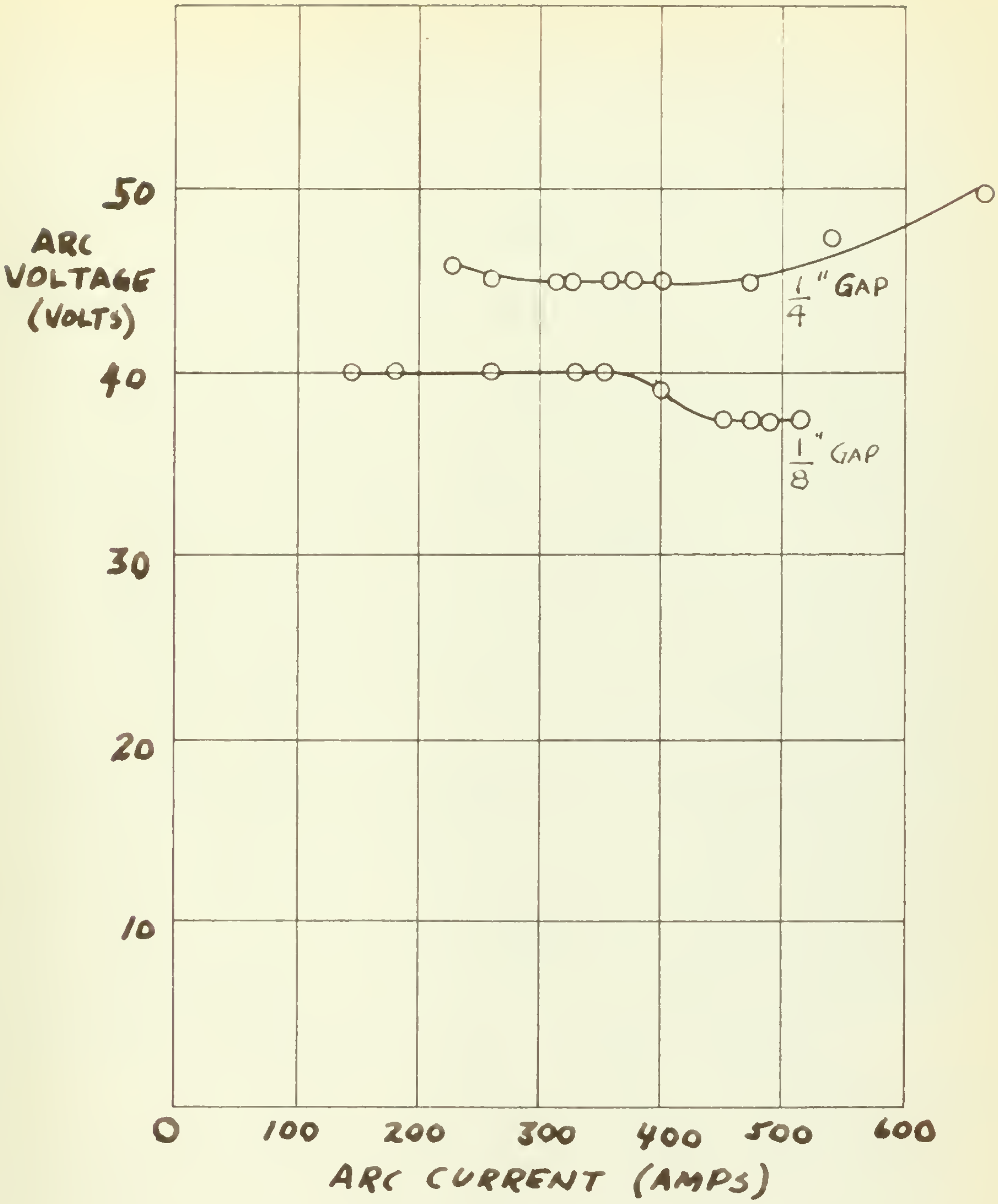
The results obtained included those shown in Figures IV and V. These volt-ampere curves were taken for various gaps, two different anode lengths and with a gas flow of 4 CFM. The arc was easy to start, stable, anode erosion was very small and quite even. Prior to taking the data shown in Figure V, the inner face of the anode was remachined removing all traces of erosion. After taking the data, the anode inner face was examined, and it exhibited negligible erosion. The sharp corners at the edge of the chamfer were intact, and the overall condition was quite good. Negligible cathode damage occured during the test.

An attempt was made to use helium instead of Argon. Full generator voltage was required to maintain the arc, and stable operation was never obtained for any gap.



VOLT-AMP CHARACTERISTICS OF A PLASMA TORCH FOR VARIOUS GAPS AND ARGON GAS AT 4 CFM LONG ($3\frac{1}{2}$") ANODE

FIG IV.



VOLT-AMP CHARACTERISTICS OF A PLASMA TORCH FOR VARIOUS GAPS AND ARGON GAS AT 4 CFM SHORT ($2\frac{1}{2}$") ANODE

FIG V

The arc reacted violently and was impossible to control. The only readings obtained with Helium were 64 volts at 800 amperes and a $\frac{1}{4}$" gap. At the conclusion of the run with Helium, the anode was examined, and deep erosion was noted in two places. No cathode damage was observed.

The P&H high frequency starter would not initiate the arc with a gap greater than 3/8" so no data were obtained for gaps above this value. No gap less than 1/8" was used as it was felt that irregularities on the anode or cathode would greatly influence gap and the arc; and that the data thus obtained would not be reproducible. As a result, all data were taken for gaps of 1/8", 1/4" and 3/8". With Argon, the arc was stable for all currents between 150 and 400 amps. The torch could be operated up to 30 seconds at 400 amperes with Argon gas which fulfilled the power input requirement of the original design. With Argon gas at a flow of 4 cubic feet per minute, negligible electrode erosion was observed. This satisfies the non-consumable electrode requirement of the original design.

An attempt was made to run the torch with the tungsten as the anode and the carbon as the cathode. Stable operation was not obtained and at the conclusion of the test, the tungsten was examined. It exhibited deep pitting around the edge.

Time did not permit quantitative temperature measurements. However, a piece of 1/16" steel was placed

$\frac{1}{2}$" in front of the long anode for about 30 seconds. It was heated red hot, but it never melted. Later, the other end of the same piece of metal was placed $\frac{1}{2}$" in front of the short anode, and a hole 5/8" in diameter was burned in it after about 15 seconds. These two tests were conducted with about 13 KW input to the torch and $\frac{1}{4}$" gap.

The gathering of data had to be stopped after taking that shown in Figure V as it became impossible to obtain reproducible data. As was previously stated, it is felt that this was caused by the oxide coating on the tungsten cathode. Attempts were made, first by wire brushing and then with emery paper, to polish the oxide coating off of the tungsten cathode. It was possible to remove the coating but after doing so, it was not possible to get reproducable data. Random variations of voltage, both above and below those previously recorded were obtained. It is felt that this was caused by contamination of the cathode.

PART V

DISCUSSION

A. Interpretation of Results

The results of this investigation indicate that it is feasible to build an inexpensive plasma arc torch that will be stable and give reproducible results using Argon gas. The arc was quite stable, anode erosion was negligible, and the only thing that limited the continuous operation of the torch was the severe heating of the anode.

The unsuccessful use of Helium was probably caused by a combination of the following facts. The ionization potential of Helium is approximately twice that of Argon. This requires more voltage across the Helium arc than the Argon arc. To give this addional voltage, the output of the generator had to be considerably increased. When the Helium arc was finally started, current up to 800 amperes was noted. This greatly increased power input, twice that originally anticipated, caused severe anode heating and damage. The failure of the carbon anode at high currents agrees with investigations[14] previously made.

The volt-ampere curves in Figure IV and Figure V exhibit a negative slope for low values of current, a minimum arc voltage drop with its zero slope and finally a positive slope as the current is increased from low to

high values. The voltage drop across the arc was increased as the gap was increased from 1/8" to 3/8". This agrees well with previous work in this area.[1,7,10,11] The curves for the short anode were flatter at the minimum points and the 1/8" gap curve showed no rising characteristic below 525 amps. It is felt that the curves, particularly the one for the 1/8" gap, of the short anode are not too reliable because of the oxide coating on the cathode appearing at the time. The attempts at melting steel definitely favor the short anode. This is reasonable because with the short anode the electrons and ions in the plasma have less chance to recombine before leaving the torch and thus are available for useful work. It would therefore appear that any torch designed for cutting should have as short an anodo as possible.

Preliminary investigations indicated that the length of plasma extending from the torch was not a function of the arc current or gap. It is felt that the distance the plasma extends from the torch is a function of gas flow.

B. Future Areas For Investigation

There are several problems connected with the plasma arc torch that bear further investigation. The first, and most obvious from the data presented here is a revision of the anode design to include more cooling. Additionally, while making a change in the anode cooling system design, it might be desirable to use another material for the anode. A water cooled anode might be made from two $\frac{1}{4}$" brass or copper plates spaced an inch or so apart in the form of a doughnut. Between these plates, it would be possible to place a spiral baffle which would allow the water to enter near the center and circulate around leaving near the edge. Also, it might be desirable to shape the orifice in the anode more along the lines of a supersonic orifice. A refinement might be the plating of the copper or brass anode described above with Tungsten to increase the anode's non-consumable property. The effects of different diameter orifices and anode lengths might also be investigated as well as improving on the anode cooling techniques.

The second area requiring further investigation is that of temperature. It is obvious that normal temperature measurement techniques are not useful in the range of temperatures existing in this device. Two methods of temperature measurement are immediately apparent. A water cooled calorimeter might be used to measure the energy in

the plasma and a heat balance used to calculate the effective temperature of the plasma. The second method would be to introduce a finely powdered material with the gas and observe the material with a spectrograph as it left the torch. If the band characteristics of the material were known, the temperature of the material would then be known. After a satisfactory method of temperature measurement is established, it will then be possible to evaluate the various torch parameters, gap, gas type and gas flow, in terms of efficient plasma generation.

A third area that invites further investigation is that of different gas types. After the anode cooling problem is solved, it should be possible to use gases other than Argon providing that a DC voltage source with an open circuit voltage of approximately 200 volts is available. If further work in this field is anticipated, a new power supply and high frequency starter should be obtained. The DC power supply should have an open circuit voltage of 200-250 volts and a current rating of 1000 amperes. The high frequency starter should be capable of breaking down a $1\frac{1}{2}''$ gap and carrying 1000 amps.

After all of the problems listed above have been satisfactorily solved, it should be possible to investigate the spraying and cutting properties of the torch as the various parameters, gas type, gas flow and gap are varied.

Additionally, it should be possible to use this torch as a plasma generator in connection with Magnetohydrodynamic experiments.

APPENDIX I

DETAILED OPERATING PROCEDURE

The operation of the torch can be broken down into three phases.

1. Preliminary
   a. Adjust cooling water flow and check for leaks.
   b. Adjust gas pressure for desired gas flow.
   c. Start DC generator and adjust the open circuit voltage for 95 volts.
   d. Adjust the gap. This is done by measuring the linear distance the cathode is moved back from anode and noting that this is the hypotenuse of a 45° right triangle. The arc gap is one of the legs of this triangle so the arc gap is the linear travel divided by $\sqrt{2}$.
2. Start-up and Operation
   a. Turn on gas and DC power to touch (Switch S1 in Figure III)
   b. Turn on high frequency starter (Switch S2 in Figure III)
   c. Turn off starter when torch fires.
   d. Adjust generator current control to give desired power input to torch.

e. Take desired readings concerning operation of torch.

3. Shutdown

a. Turn off gas and DC to torch (Switch S1 in Figure III)

b. Turn off generator

c. Turn off all circuit breaker feeding the equipment and turn off gas at the cylinder.

d. Turn off cooling water but only after anode is no longer hot to the touch.

Switch S1 shown in Figure III should be kept readily at hand since it can be used to stop the torch immediately in case of trouble.

PART VII

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